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DETECTION AND CHARACTERIZATION OF PLANETS IN BINARY AND MULTIPLE SYSTEMS

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Abstract. Moderately close binaries are a special class of targets for planet searches. From a theoretical standpoint, their hospitality to giant planets is uncertain and debated. From an observational standpoint, many of these systems present technical difficulties for precise radial-velocity measurements and classical Doppler surveys avoid them accordingly. In spite of these adverse factors, present data support the idea that giant planets residing in binary and hierarchical systems provide unique observational constraints on the processes of planet formation and evolution. The interest and the importance of including various types of binary stars in extrasolar planet studies have thus grown over time and significant efforts have recently been put into: (i) searching for stellar companions to the known planet-host stars using direct imaging, and (ii) extending Doppler planet searches to spectroscopic and moderately close visual binaries. In this contribution we review the observational progresses made over the past years to detect and study extrasolar planets in binary systems, putting special emphasis on the two developments mentioned above.

1 Introduction

Nearby G-K dwarfs, which are first-choice targets for many planet search programs, are more often found in binary or multiple systems than in isolation (e.g. Duquennoy & Mayor 1991; Eggenberger et al. 2004a). This observation, coupled with the growing evidence that many young binaries possess circumstellar or circumbinary disks susceptible of sustaining planet formation (e.g. Monin et al.

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2007), raises the question of the existence of planets in star systems of different types.

From a dynamical standpoint, planets residing in binary systems can be found in three different configurations: (1) in circumstellar orbits (i.e. orbiting the primary or the secondary star, also called S-type orbits); (2) in circumbinary orbits (i.e. circling both stars, P-type orbits); or (3) around the L4 or L5 Lagrange point in systems with a very small mass ratio (Trojan planets, L-type orbits). However, the presence of an additional stellar companion may threaten either the formation or the long-term stability of planetary systems, imposing further restrictions. For instance, a stellar companion within $\sim$100 AU will likely affect – and possibly inhibit – the formation of circumstellar giant planets (e.g. Nelson 2000; Mayer et al. 2005; Thébault et al. 2006; see also the contributions by Kley, Marzari, and Thébault), while a more distant but highly inclined companion can influence the evolution of these planets on secular timescales (e.g. Innanen et al. 1997; Takeda & Rasio 2005). These considerations raise two fundamental questions: What types of binary systems do actually host planets in S/P/L-type orbits?, and Are such planets common or rare?

Most of the information we presently have about planets in binaries comes from "classical" Doppler planet searches which target nearby G-K dwarfs. This observational material is highly incomplete with respect to the closest binaries, however, because it is difficult to extract precise radial velocities when the two components simultaneously contribute to the recorded flux (Eggenberger & Udry 2007). To avoid light contamination at the spectrograph entrance, Doppler surveys exclude from their target samples most – but usually not all – double stars closer than 2-6$''$ (e.g. Udry et al. 2000; Perrier et al. 2003; Marcy et al. 2005; Jones et al. 2006), systems which we will call moderately close binaries. This strategy implies that classical Doppler programs provide little information about the existence of planets in spectroscopic and visual binaries $\lesssim$200 AU. To probe the occurrence of planets in these moderately close systems, new methods and alternative detection techniques have been actively developed over the past years.

This chapter is partly a review on the observational efforts to detect and characterize extrasolar planets in binary systems, and partly a description of our own contribution to this research field. In Sect. 2 we present a brief overview of the methods that are being used to detect extrasolar planets in binary and multiple systems. In Sect. 3 we summarize the information gathered on planets in binaries through classical Doppler planet searches. We then describe our recent efforts to investigate the impact of stellar duplicity on the occurrence and properties of giant planets. This work follows two complementary approaches: searching for stellar companions to the known planet-host stars using direct imaging (Sect. 4), and extending Doppler planet searches to spectroscopic binaries (Sect. 5). We conclude in Sect. 6 with a summary of the main results and future perspectives.

2 Observational methods to detect extrasolar planets in binary systems

The interest for planets in binaries increased rapidly in ∼2002 following two important discoveries. Firstly, two giant planets were detected in the spectroscopic binaries GJ 86 (Queloz et al. 2000) and γ Cephei (Hatzes et al. 2003), bringing evidence that circumstellar Jovian planets do exist in systems separated by ∼20 AU. Secondly, Zucker & Mazeh (2002) pointed out that planets found in binaries seem to follow a different period-mass correlation than planets orbiting single stars. This led to the idea that planets found in binary and multiple systems may provide unique testing grounds for the models of planet formation and evolution.

Since ∼2002, a few Doppler planet searches targeting exclusively spectroscopic and visual binaries have been initiated to complement the observations from classical surveys (see also Sect. 5, and the contributions by Konacki and Desidera). Programs searching for circumstellar planets in visual binaries $\gtrsim$100 AU (Desidera et al. 2007; Toyota et al. 2009) treat their targets as two single stars and face little technical difficulty. An attractive aspect of these programs is their ability to probe possible differences in the chemical composition of solar-type stars with and without planetary systems. Doppler surveys dedicated to planet searches in spectroscopic and moderately close visual binaries (Eggenberger et al. 2003; Konacki 2005b; Toyota et al. 2005; Eggenberger & Udry 2007) are much more challenging technically (the two stars cannot be observed individually), but can potentially bring fundamental information for planet formation theories. Using the same technique but different target samples, these surveys can search either for circumstellar planets in binaries $\lesssim$50 AU, or for circumbinary planets around close binaries (∼0.05-0.5 AU). None of these dedicated Doppler programs has detected a reliable planet candidate so far, but all the surveys are still ongoing.

Like Doppler spectroscopy, transit photometry works normally with regard to planet searches around the components of wide binaries, but faces additional challenges with moderately close systems. Yet, eclipsing binaries represent an attractive class of targets for the photometric method. On the one hand planetary transits are more likely to occur is these edge-on systems, and high-precision photometry should allow the detection of transiting circumstellar, circumbinary (Deeg et al. 1998; Doyle et al. 2000; Ofir 2008), and Trojan planets (Caton et al. 2000). On the other hand, the same photometric data can be used to search for nontransiting giant planets in circumbinary orbits through the precise timing of eclipse minima (Deeg et al. 2000, 2008; Lee et al. 2009). To date, planet searches in eclipsing binaries have detected a pair of circumbinary substellar objects (minimum masses of 19.2 and 8.5 M_{Jup}) around HW Virginis (Lee et al. 2009) and a possible circumbinary planet around CM Draconis (Deeg et al. 2008).

Given a sufficient time baseline, pulse timing measurements provide a good dynamical description of nearly any type of multiple system orbiting a neutron star that can be timed with a microsecond precision. For instance, the series of timing data of PSR B1620-26 indicates that this millisecond pulsar belongs to a hierarchical triple system, with a circumbinary planet orbiting the inner pulsar – white dwarf pair (Thorsett et al. 1999; Ford et al. 2000a; Sigurdsson & Thorsett

2005). Pulsar timing and photometry of eclipsing binaries are currently the only two methods that can detect low-mass planets in/around binary systems.

According to recent modeling work, the signatures of both a planet and a binary companion can be detected under certain conditions in the light curves of high-magnification microlensing events. In particular, the microlensing technique should be able to identify circumstellar giant planets in binary systems $\lesssim$100 AU (Lee et al. 2008), or Jupiter-mass circumbinary planets orbiting binaries separated by $\sim$0.15-0.5 AU (Han 2008). In the future, microlensing searches may thus enrich the samples of planets residing in and around (moderately) close binaries.

Astrometry is intrinsically well suited to search for planets in some types of moderately close binaries, the secondary star providing a convenient positional reference. Relative astrometry has the advantage of yielding the full planetary orbit and the planet's true mass, but the disadvantage of not distinguishing between circumprimary and circumsecondary planets. Since 2003 the PHASES program has used the phase-referencing technique at the Palomar Testbed Interferometer to search for circumstellar giant planets among $\sim$50 binaries with a median separation of 19 AU (Lane & Muterspaugh 2004; Muterspaugh et al. 2006a). Contrary to Doppler spectroscopy, astrometry is mostly sensitive to long-period companions, and the two methods nicely complement to probe the occurrence of giant planets in moderately close binaries. Current results from the PHASES program exclude the presence of giant planets in 8 systems from its target list (Muterspaugh et al. 2006b).

Narrow-field, adaptive optics imaging may be an alternative means to perform relative astrometry of moderately close binaries with a precision good enough to detect circumstellar massive planets (see the contributions by Hełminiak and Roell). Since this method is particularly well suited to study binary systems separated by a few arc seconds, it would offer the possibility of deriving the true mass of some of the giant planets detected by classical Doppler surveys. Although encouraging results have recently been reported for short-term observations (Neuhäuser et al. 2007; Hełminiak & Konacki 2008; Roell et al. 2008), the technical and practical feasibility of this approach remains to be demonstrated in the long term.

3 Results from classical Doppler planet searches

3.1 *The sample of planets in binaries*

Thanks to classical Doppler surveys and to complementary searches for common proper motion companions to planet-host stars (Sect. 4), the number of planets known to orbit a component of a binary or multiple star has grown rapidly in the past few years and now outnumbers 53 planets in 45 planetary systems (e.g. Eggenberger & Udry 2007). Most of these planets are gas giants ($>$0.3 $M_{\rm Jup}$), which mainly reflects the high sensitivity of the Doppler technique to massive companions. In terms of system architecture, these planets reside in binary or hierarchical systems with projected separations between $\sim$20 AU and $\sim$12000 AU, and almost all of them orbit the primary component. This last feature is partly

a selection effect, the secondaries being often too faint to belong to the target samples used by Doppler programs. Due to their discrimination against the closest binaries, classical programs do not provide us with much information about the existence of circumbinary planets. Nonetheless, one candidate may have been found (Correia et al. 2005).

Only a handful of the known planets reside in binaries $\lesssim$100 AU, making giant planets apparently rarer in these systems than in wider pairs or around single stars. Although some theoretical models predict a shortage of giant planets precisely in binaries $\lesssim$100 AU (Nelson 2000; Mayer et al. 2005; Thébault et al. 2006), the small number of planetary detections in these systems results at least partly from the selection effects mentioned in Sect. 1. Another interesting feature visible in the data from Doppler surveys is the lack of circumstellar planets in binaries $\lesssim$ 20 AU. According to theoretical models the formation of giant planets is severely hampered in these systems (Nelson 2000; Thébault et al. 2004; Mayer et al. 2005; Boss 2006; Thébault et al. 2006), which suggests that the "limit" at 20 AU might have a true meaning. Yet, the present observational material does not allow us to rule out the alternative hypothesis that the lack of planetary detections in systems $\lesssim$20 AU simply reflects the discrimination against "short-period" ($\lesssim$10 years) spectroscopic binaries.

To sum up, classical Doppler surveys have brought evidence that at least 17% of the known planetary systems are associated with one or more stellar companion. However, due to noticeable selection effects against moderately close binaries, the data from these surveys cannot be used to derive the true frequency of planets in binaries $\lesssim$100 AU, nor to probe the existence of planets in binaries $\lesssim$20 AU. To investigate these two fundamental questions we need planet search programs capable of dealing with moderately close binaries. We discuss our own Doppler surveys and some of their preliminary results in Sect. 5.

3.2 *Different properties for planets in binaries?*

Following Zucker & Mazeh (2002), who pointed out that planets in binaries seem to follow a different period-mass correlation than planets orbiting single stars, we performed in 2004 a statistical study considering both the period-mass and the period-eccentricity diagrams (Eggenberger et al. 2004b). As shown in Fig. 1 (left), our analysis confirmed that the few most massive ($M_2 \sin i \gtrsim 2$ $\mathrm{M_{Jup}}$) short-period ($P \lesssim 40$ days) planets all orbit a component of a binary or multiple star. However, the inclusion of several new planets in binaries with periods >100 days and minimum masses in the range 3–5 $\mathrm{M_{Jup}}$ decreased the significance of the negative period-mass correlation found by Zucker & Mazeh (2002). More recent studies confirm this trend (Desidera & Barbieri 2007; Mugrauer et al. 2007), leaving as a robust feature only the observation that the few most massive short-period planets are all found in binary or multiple systems.

Regarding the period-eccentricity diagram, our analysis emphasized that the planets with a period $P \lesssim 40$ days and residing in binaries tend to have low eccentricities ($e \lesssim 0.05$) compared to their counterpart orbiting single stars (Fig. 1,

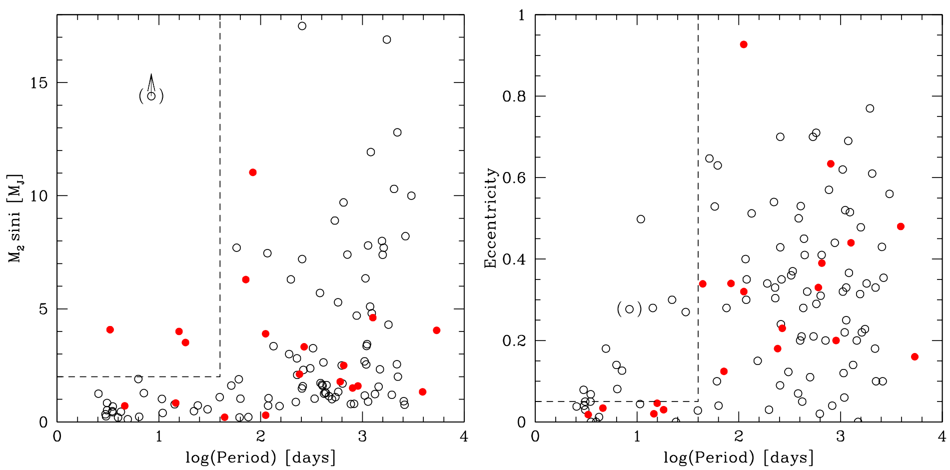

Fig. 1. Left: Minimum mass vs orbital period for all the extrasolar planetary candidates known in 2004. Planets orbiting a single star are represented as open circles, while planets residing in binary or multiple systems are represented as dots. The dashed line approximately delimits the zone where only extrasolar planets belonging to binaries are found. **Right:** Eccentricity vs orbital period for the same planetary candidates as before. The dashed line approximately delimits the region where no planet-in-binary is found.

right). The confirmation – or refutation – of this trend looks more tricky (Desidera & Barbieri 2007; Mugrauer et al. 2007), probably because several different mechanisms play a role in shaping the eccentricity distribution of extrasolar planets. We plan to revisit this question once we will have in hands the final results from our two imaging programs (Sect. 4).

Another intriguing feature is the observation that the four planets with the highest eccentricities ($e > 0.8$) all have a stellar or brown dwarf companion (Tamuz et al. 2008). This association likely points towards eccentricity excitation by the Kozai mechanism (Wu & Murray 2003; Takeda & Rasio 2005; Moutou et al. 2009). The Kozai mechanism is a secular interaction which operates in hierarchical triple systems with high relative inclination, causing large-amplitude periodic oscillations of the eccentricity of the inner pair (e.g. Holman et al. 1997; Innanen et al. 1997; Mazeh et al. 1997; Ford et al. 2000b). If distant stellar companions commonly induce Kozai oscillations in planetary systems, this should produce a small excess of very eccentric orbits among the population of planets in binaries (Takeda & Rasio 2005), which is precisely what Tamuz et al. (2008) pointed out.

The three trends outlined above are very interesting because they may shed light on the origin of some of the short- and intermediate-period planets. Recent theoretical work has shown that the coupling of Kozai oscillations with tidal friction (sometimes called Kozai migration) can produce eccentric planets on intermediate orbits (Wu & Murray 2003), but also short-period planets on (nearly) cir-

cular orbits such as the hot Jupiters (Fabrycky & Tremaine 2007; Wu et al. 2007). Interestingly, this migration mechanism specific to multi-body systems could be more effective than type II migration in bringing massive planets to the vicinity of their host star. Kozai migration triggered by a distant stellar companion may thus explain why the most massive short-period planets are all found in binary or multiple systems (Takeda & Rasio 2006; Fabrycky & Tremaine 2007). According to some authors, Kozai migration might also circularize planetary orbits to greater orbital periods (Fabrycky & Tremaine 2007), thereby explaining the trend seen in the eccentricity-period diagram.

To put the above observational results on firmer statistical grounds, future investigations will have to improve on three points: (1) to enlarge the sample of short-period planets found in binaries, (2) to systematically probe the presence of stellar companions to planet-host stars, and (3) to correct for the selection effects against moderately close binaries. We describe in the next two sections our efforts to tackle these issues with the aim of better understanding the impact of stellar duplicity on the occurrence and properties of giant planets.

4 Results from our imaging surveys

Theoretical work indicates that the main issue regarding the occurrence of circumstellar giant planets in binaries $\lesssim$100 AU is whether these planets can form in the first place. Interestingly, the two mechanisms susceptible of forming giant planets – core accretion and disk instability – may exhibit a different sensitivity to the presence of a moderately close stellar companion (Nelson 2000; Mayer et al. 2005; Boss 2006; Thébault et al. 2006). In particular, it has been suggested that giant planets formed by disk instability should be rare in binaries separated by 60-100 AU, while giant planets formed by core accretion should be common in these same systems (Mayer et al. 2005). In practice, dynamical interactions may complicate this simple picture by depositing a few giant planets in systems originally void of any (Pfahl 2005; Portegies Zwart & McMillan 2005; Pfahl & Muterspaugh 2006). Nonetheless, quantifying the occurrence of circumstellar giant planets in binaries $\lesssim$100 AU and studying how this occurrence varies with binary separation is fundamental to understanding planet formation.

As mentioned previously, the data from classical Doppler surveys cannot be used to derive the true frequency of planets in binaries $\lesssim$100 AU. However, the problem of quantifying the impact of stellar duplicity on planet occurrence can be tackled in an indirect way, by comparing the multiplicity among planet-host stars to the multiplicity among similar stars but without planetary companions. Indeed, if the presence of a nearby stellar companion hinders (favors) planet formation, the frequency of circumstellar planets in binaries closer than a given separation – modulo eccentricity and mass ratio – should be lower (higher) than the nominal frequency of planets around single stars. That is, the binary fraction among planet-host stars should be smaller (larger) than the binary fraction among single stars. Note that such a comparison requires the use of a well-defined control sample to: (i) take into account the selection effects against moderately close binaries in

Doppler planet searches, and (ii) compare the multiplicity among planet-host stars with the multiplicity among similar stars but without planetary companions.

Since 2002 direct imaging has been used by several groups to detect new stellar companions to planet-host stars (Luhman & Jayawardhana 2002; Patience et al. 2002; Chauvin et al. 2006; Mugrauer et al. 2007; see also the contribution by Mugrauer). In addition, astronomical catalogs and multiepoch images from the STScI Digitized Sky Survey have been searched for unrecognized stellar companions to the known planet-host stars (Raghavan et al. 2006; Desidera & Barbieri 2007). While these surveys have revealed many new binary and multiple systems among planet-host stars, they cannot draw reliable conclusions about the impact of stellar duplicity on planet occurrence because they lack a well-defined control sample of non-planet-bearing stars.

To test whether the frequency of circumstellar giant planets is reduced in binaries $\lesssim$100 AU, we have conducted a large-scale adaptive optics search for stellar companions to $\sim$200 solar-type stars with and without planets (Eggenberger et al. 2007a). Our main program is divided into two subprograms: a southern survey (130 stars) carried out with NAOS-CONICA (NACO) on the Very Large Telescope, and a northern survey ($\sim$70 stars) carried out with PUEO on the Canada-France-Hawaii Telescope. The NACO survey is now completed, while the PUEO survey is still halfway. We discuss below the results from our NACO survey.

4.1 The NACO survey

The NACO survey relies on a subsample of 57 planet-host stars, and on a control subsample of 73 dwarfs from the CORALIE planet search program showing no obvious evidence for planetary companions from radial-velocity measurements. Note that selecting the control stars within the CORALIE sample naturally ensures that we match the target selection criteria for Doppler planet searches. To avoid duplicating existing observations, we excluded from our survey most of the planet-host stars observed by Patience et al. (2002) and Chauvin et al. (2006). These stars are included in our statistical analysis, though, which finally balances the two subsample sizes to $\sim$70 stars each.

Our NACO data revealed 95 companion candidates in the vicinity of 33 targets. On the basis of two-epoch astrometry we identified 19 true companions, 2 likely bound objects, and 34 background stars (Eggenberger et al. 2007a). Among planet-host stars, we discovered two very low mass companions to HD 65216, an early-M companion to HD 177830, and we resolved the previously known companion to HD 196050 into a close pair of M dwarfs. Our data additionally confirm the bound nature of the companions to HD 142, HD 16141, and HD 46375. The remaining 11 true companions and the two likely bound objects all orbit control stars. These objects are either late-K stars or M dwarfs, and have projected separations between 7 and 505 AU.

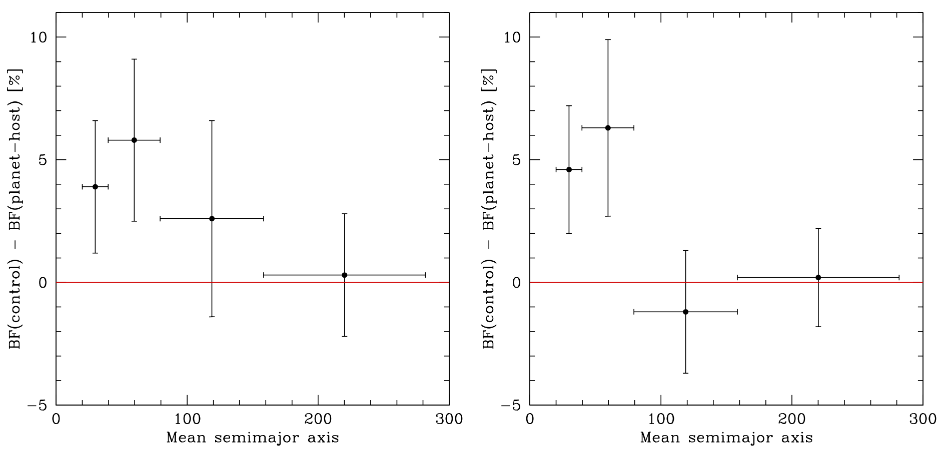

Fig. 2. Difference (in percent) between the binary fraction among control stars and the binary fraction among planet-host stars vs binary mean semimajor axis. The left plot is based on the redefined subsamples, while the right plot is based on the full subsamples.

4.2 The impact of stellar duplicity on the occurrence of giant planets

A potentially sensitive point in estimating the impact of stellar duplicity on the occurrence of circumstellar planets is the exact definition of the control subsample. The main issue is that a small amplitude radial-velocity drift can just as well be the signature of a planet as that of a more distant stellar companion. By being too severe on the selection of non-planet-host stars we may thus also exclude the closest binaries from the control subsample and bias the analysis. To test the sensitivity of our results to the definition of each subsample, we performed a first analysis based on two different sample redefinitions: (i) a loose redefinition where both subsamples were little modified except for an homogeneous cut-off at close separation ($\sim 0.7''$); (ii) a more stringent redefinition where both subsamples were limited in distance to 50 pc, and where control stars showing any type of radial-velocity variation were rejected (see Eggenberger et al. 2008 for further details).

According to our data, the binary fraction among planet-host stars is $5.5 \pm 2.7\%$ (4/73) for the full subsample and $4.9 \pm 2.7\%$ (3/62) for the redefined subsample. For control stars, we obtain binary fractions of $13.7 \pm 4.2\%$ (9/66) and $17.4 \pm 5.2\%$ (9/52) for the full and redefined subsamples, respectively. These results translate into a difference in binary fraction (control − planet-host) of $8.2 \pm 5.0\%$ for the full subsample and of $12.5 \pm 5.9\%$ for the redefined one. Although the relative errors on these results are quite large due to the small number of available companions, both sample definitions yield a positive difference with a statistical significance of 1.6-2.1σ. This positive difference means that circumstellar giant planets are less frequent in binaries with mean semimajor axes between 35 and 250 AU than around single stars.

To push the investigation a step further and to seek for a possible trend with mean semimajor axis, we computed the difference in binary fraction for a few bins in separation between 20 and 280 AU. The results for both subsamples are displayed in Fig. 2. These two plots show that the difference in binary fraction is not spread uniformly over the semimajor axis range studied, but seems concentrated below $\sim$100 AU. This result is very interesting because it may corroborate the theoretical studies which predict a negative impact of stellar duplicity on the formation of circumstellar giant planets in binaries $\lesssim$100 AU. At any rate, the statistical analysis presented here goes beyond what has been done so far, as the former analyses (Patience et al. 2002; Raghavan et al. 2006; Bonavita & Desidera 2007; see also the contribution by Bonavita) could not correct their results for the selection effects of Doppler surveys against moderately close binaries.

5 Results from our Doppler planet searches in spectroscopic binaries

Doppler data of binaries $\lesssim$2–6$''$ consist generally not of a single stellar spectrum, but of a composite spectrum made of two stellar spectra. Obviously, this introduces some complications into the extraction of the radial velocity, rendering classical cross-correlation techniques not well adapted to search for planets in (moderately) close systems (Eggenberger & Udry 2007; see also the contribution by Marmier). A better way to extract precise radial velocities for the individual components of spectroscopic binaries is to generalize the concept of one-dimensional cross-correlation to that of two-dimensional correlation. This approach was followed some time ago by Zucker & Mazeh (1994), who developed a two-dimensional correlation algorithm named TODCOR. This algorithm has recently been generalized to multiorder spectra (Zucker et al. 2003; Zucker 2003) and we are now using it to search for planets in spectroscopic and moderately close visual binaries.

We present in this section some results from our ongoing searches for circumstellar planets in spectroscopic binaries. Our presentation will follow an increasing order of difficulty in terms of radial-velocity extraction, starting with the easiest systems that are single-lined spectroscopic binaries (SB1s, where only the spectrum of the primary star is detected) and ending with the more complicated double-lined spectroscopic binaries (SB2s, where the spectra of both components are detected).

5.1 Planet searches in single-lined spectroscopic binaries

To quantify the occurrence of circumstellar giant planets in the closest binaries susceptible of hosting them, we initiated in 2001 a Doppler search for short-period circumprimary planets in SB1s (e.g. Eggenberger et al. 2003; Eggenberger & Udry 2007). The restriction of our survey to SB1s was mainly motivated by the higher prospect of finding circumstellar giant planets in these systems than in SB2s, which have similar separations but more massive secondaries.

Our sample of SB1s consists of 101 systems selected on the basis of former CORAVEL surveys carried out to study the multiplicity among nearby G and K dwarfs (Duquennoy & Mayor 1991; Halbwachs et al. 2003). All our binaries have

a period of more than 1.5 year, but not all of them have a well-characterized orbit; the systems with the longest orbital periods (a few to several tens of years) only show long-period drifts in radial velocity. Since CORAVEL velocities have a typical precision of 300 $\mathrm{m\,s^{-1}}$ they cannot be used to search for planets. To this purpose we took 10 to 15 additional high-precision radial-velocity measurements of each system with the ELODIE spectrograph for the northern targets, and with the CORALIE spectrograph for the southern systems.

5.1.1 First analysis based on one-dimensional cross-correlation

When searching for circumstellar planets in spectroscopic binaries we are interested in short-period variations not in the radial velocities themselves but in the residual (radial) velocities around the binary orbits. In practice we quantify these variations by a normalized root-mean-square (rms), which is the ratio of the external error (i.e. the standard deviation around the orbit or around the drift) to the mean internal error (i.e. the mean of individual photon-noise errors). According to our data, most of our targets (74%) have a normalized rms close to 1, which indicates that no source of radial-velocity variation other than the orbital motion is present. However, 12.5% of our binaries are clearly variable (normalized rms > 3), while 13.5% of them are marginally variable (normalized rms between 2 and 3).

In terms of planetary prospects, the most interesting systems are the variable and marginally variable binaries. Yet, the presence of a circumprimary planet is not the only way to produce residual-velocity variations like those observed. Alternative possibilities include: (i) the primary star is intrinsically variable, (ii) the system is an unrecognized SB2 (i.e. an SB1 when analyzed with one-dimensional cross-correlation, but an SB2 when analyzed with two-dimensional correlation), and (iii) the system is in fact triple and the secondary is itself a short-period spectroscopic binary. Assuming that planets are as common in moderately close binaries as around single stars, we expect to find $\sim$2 planets more massive than 0.5 $\mathrm{M_{Jup}}$ and with a period $\lesssim$40 days in our sample. This estimation shows that most of the observed residual-velocity variations likely stem from the binary or multiple nature of our targets. To disentangle the few potential planet-host stars from the unrecognized SB2s and triple systems, we are analyzing all the variable and marginally variable systems with the TODCOR algorithm.

5.1.2 Complementary analysis based on two-dimensional correlation

Among the four variable binaries studied in detail so far, two turned out to be triple systems (see Fig. 3 for an example) and the two others turned out to be unrecognized SB2s. None of these systems shows hints of the presence of a circumprimary planet.

5.1.3 Preliminary statistical results

In 74% of our SB1s the secondary component is so faint (magnitude difference $\Delta V \gtrsim 6$) that it does not contribute significantly to the recorded flux. The precision

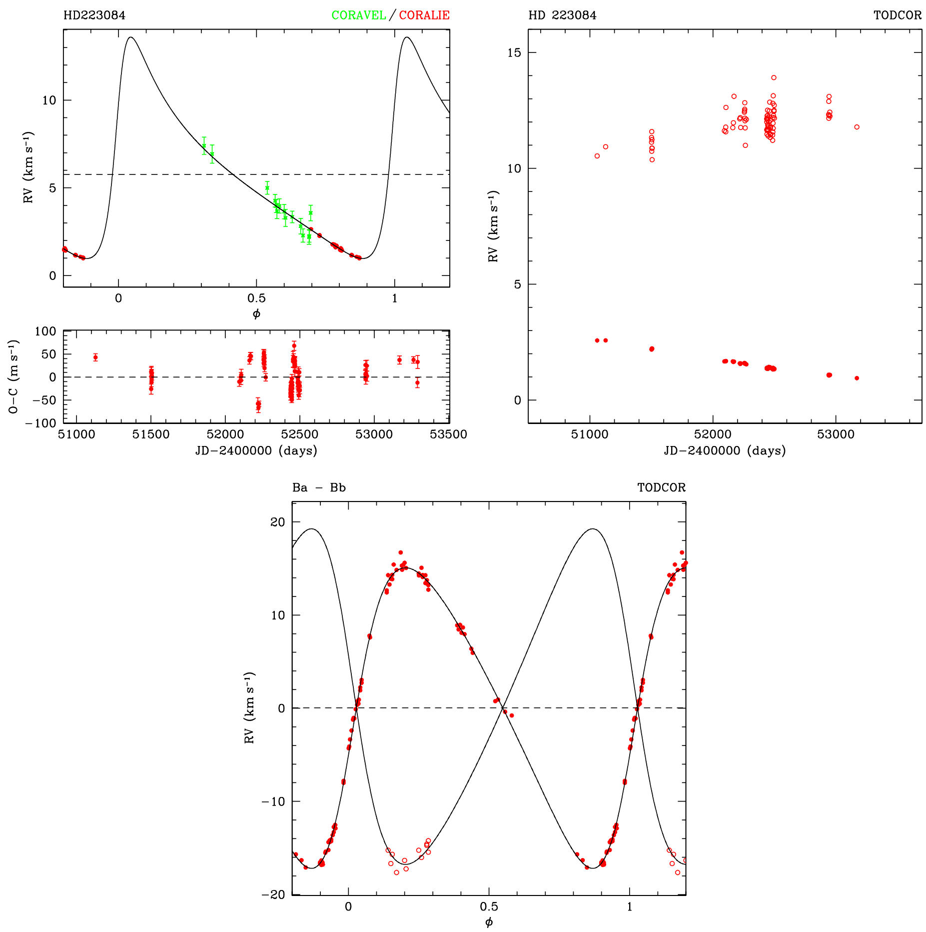

Fig. 3. An example of triple system: HD 223084. **Top left:** CORAVEL (crosses, large error bars) and CORALIE (dots) velocities for HD 223084. The binary orbit is tentative and is used only as a proxy to compute residual velocities. The bottom panel shows the residual velocities (CORALIE data only). **Top right:** TODCOR velocities for HD 223084 A (dots) and HD 223084 Ba (open circles) after having removed the 202-day modulation of the Ba–Bb inner pair. **Bottom:** SB2 orbit for HD 223084 Ba (dots) and HD 223084 Bb (open circles). This orbit is characterized by a period of 202 days.

achieved on the measurement of the radial velocity of the primary star is then as good as for single stars. In 26% of our binaries, the secondary component contributes to some extent to the recorded flux ($\Delta V \in [\sim 3, \sim 6]$), rendering the use of two-dimensional correlation mandatory to search for circumprimary planets. For these systems, we estimate that typical precisions on the radial velocity of the

primary star range from 10 to 20 m s^{-1}. Although these precisions are not as good as for single stars, they remain good enough to search for giant planets.

So far our survey has unveiled no promising planetary candidate, but the data of 22 variable and marginally variable systems remain to be analyzed in detail with two-dimensional correlation. Since contamination effects stemming from the stellar companions are likely to prevail over potential planetary signals, two-dimensional analyses must be completed before concluding on the existence – or absence – of planets in our sample. All we can say at present is that less than 22% of the SB1s from our sample host a short-period ($P \lesssim 40$ days) giant ($M_2 \sin i \gtrsim 0.5$ $M_{\rm Jup}$) circumprimary planet. The final analysis will provide a much stronger constraint on the frequency of short-period giant planets in SB1s.

5.2 *Planet searches in double-lined spectroscopic binaries*

SB2s have not been systematically included in any of our programs yet, but we are conducting a series of observational tests to characterize the feasibility of Doppler planet searches in and around these systems. As an illustration of this work, we present here the results we have obtained for our best-studied case, the triple system HD 188753 (Eggenberger et al. 2007b).

5.2.1 The example of HD 188753

HD 188753 has attracted much attention since Konacki (2005a) reported the discovery of a Jovian planet on a 3.35-day orbit around the primary component of this triple system. Aside from the planet, HD 188753 consists of a visual pair (HD 188753 A and HD 188753 B) with a semimajor axis of 12.3 AU (0.27″ separation) and an eccentricity of 0.5 (Söderhjelm 1999). In addition, component B is itself a spectroscopic binary (i.e. HD 188753 B is composed of HD 188753 Ba and HD 188753 Bb) with a period of 155 days (Griffin 1977; Konacki 2005a). What renders this planet discovery particularly noteworthy is that according to the canonical models of planet formation the periastron distance of the AB pair may be small enough to preclude giant planet formation around HD 188753 A (Nelson 2000; Mayer et al. 2005; Boss 2006; Jang-Condell 2007). The discovery of a close-in giant planet around this star has thus been perceived as a serious challenge to planet-formation theories, though the alternative possibility that HD 188753 A may have acquired its planet through dynamical interactions was also pointed out (Pfahl 2005; Portegies Zwart & McMillan 2005).

Following the discovery announcement, we monitored HD 188753 with the ELODIE spectrograph during one year. Our TODCOR velocities for the two brightest components – HD 188753 A and HD 188753 Ba – are displayed in Fig. 4. Using two-dimensional correlation, the spectrum of the faintest component is undetectable in most of our observations. Our measurements confirm that HD 188753 Ba is a spectroscopic binary with a period of 155 days. However, our radial velocities for HD 188753 A show no sign of the 3.35-day planetary signal reported by Konacki (2005a). Instead, the residuals around the velocity drift due to the orbital motion

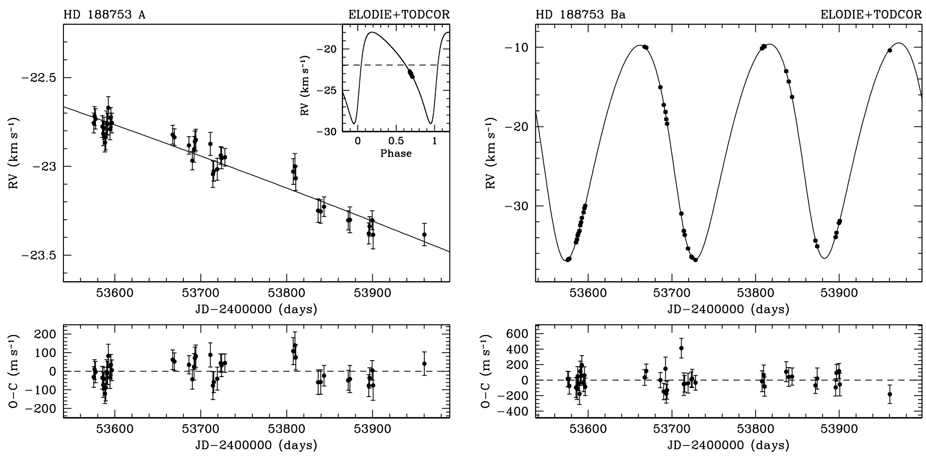

Fig. 4. Radial velocities and orbital solutions for HD 188753 A (left) and HD 188753 Ba (right). For component A, the solid line represents the 25.7-year orbital motion of the visual pair shown in full in the inset. For component Ba, the orbital solution corresponds to the 155-day modulation and it includes a linear drift to take the 25.7-year orbital motion into account.

of the AB pair are basically noise, and the rms of 60 $\mathrm{m\,s^{-1}}$ can be interpreted as the precision we achieve on the measurement of the radial velocity of this star. Monte Carlo simulations showed that we had both the precision and the temporal sampling required to detect a planetary signal like the one described by Konacki (2005a). On that basis, we conclude that our ELODIE data show no evidence of a 1.14-$\mathrm{M_{Jup}}$ planet on a 3.35-day orbit around HD 188753 A.

Besides the question of whether there is a hot Jupiter around HD 188753 A, our analysis of HD 188753 raises several issues. In particular, the precision of 60 $\mathrm{m\,s^{-1}}$ obtained on the radial velocity of HD 188753 A looks abnormally poor compared to the results presented in Sect. 5.1. The most probable explanation is that the search for circumprimary planets in SB2s requires higher quality data (mainly a better spectral resolution) than the search for circumprimary planets in SB1s. The new data set of HD 188753 we have just acquired with the SOPHIE spectrograph (spectral resolution of 75,000 against 40,000 for ELODIE) will help clarify this point. But these new data will not likely change our conclusion that there is no supporting evidence for the claimed hot Jupiter around HD 188753 A.

5.2.2 Outlook

Including SB2s in Doppler planet searches is desirable for two reasons. Firstly, the frequency of circumstellar giant planets residing in these systems would provide important constraints for planet formation theories. Secondly, some SB2s are the potential targets for circumbinary planet searches, which constitute a still largely

unexplored research field worth of interest. As illustrated above, deriving radial velocities for the individual components of SB2s to the precision needed to search for planets is challenging. A few different methods are currently being tested to determine the most efficient way to overcome this challenge and the main limiting factors associated with each method. Current results indicate that the prospects of using Doppler spectroscopy to search for giant planets in SB2s are promising, provided one has good enough data (see e.g. the contribution by Konacki).

6 Conclusion and perspectives

Over the past seven years, binaries have become increasingly interesting targets for planet searches. From the observational perspective, Doppler surveys have shown that at least 17% of the known planetary systems are associated with one or more stellar companions (e.g. Eggenberger & Udry 2007) and that circumstellar giant planets exist in binaries as close as 20 AU (Queloz et al. 2000; Hatzes et al. 2003; Zucker et al. 2004; Correia et al. 2008). From the theoretical perspective, simulations indicate that the presence of a stellar companion within $\sim$100 AU likely affects the formation and evolution of circumstellar giant planets (Kley 2000; Nelson 2000; Mayer et al. 2005; Boss 2006; Thébault et al. 2006), leaving potential imprints in the occurrence and properties of these objects. Circumstellar planets residing in binaries $\lesssim$100 AU thus provide unique testing grounds for the models of planet formation and evolution.

Imaging and literature surveys searching for stellar companions to the known planet-bearing stars have been very successful, revealing many new binary and multiple planet-host systems (e.g. Patience et al. 2002; Raghavan et al. 2006; Chauvin et al. 2006; Desidera & Barbieri 2007; Eggenberger et al. 2007a; Mugrauer et al. 2007). Thanks to its well-defined control sample, our NACO survey provides the first piece of evidence that circumstellar giant planets are intrinsically less frequent in binaries $\lesssim$100 AU than around single stars (Eggenberger et al. 2008). Future analyses based on larger samples will constrain the dependence of this frequency on binary separation over the range $\sim$35-250 AU.

The discoveries from classical Doppler planet searches and from imaging surveys indicate that the Kozai mechanism plays a role in shaping the high end of the eccentricity distribution of extrasolar planets (Wu & Murray 2003; Takeda & Rasio 2005; Tamuz et al. 2008; Moutou et al. 2009). Additionally, the distinctive properties of the short-period planets residing in binary or hierarchical systems (Zucker & Mazeh 2002; Eggenberger et al. 2004b; Desidera & Barbieri 2007; Mugrauer et al. 2007) suggest that some of these planets owe their current orbital configuration to Kozai migration (Takeda & Rasio 2006; Fabrycky & Tremaine 2007; Wu et al. 2007). The data set on planets in binaries thus provides growing evidence that distant stellar companions commonly affect the orbital evolution of planetary systems on secular timescales.

Since 2002 significant efforts have been put into extending planet searches to (moderately) close binaries using different techniques, including Doppler spectroscopy, phase-referenced interferometry, eclipse or pulse timing, transit photom-

etry, gravitational microlensing, and adaptive optics imaging. Although these efforts have not produced many planet discoveries yet, they will yield very important results in the coming years. Upon completion, the ongoing Doppler and interferometric surveys will provide the first measures of the true frequency of circumstellar planets in binaries $\lesssim$50 AU. When combined with the results from imaging programs, these new data will give some information as to whether circumstellar giant planets commonly form in binaries $\lesssim$100 AU. At the same time, the present and future Doppler surveys targeting SB2s will quantify the frequency of massive circumbinary planets.

In the next few years, several additional observing facilities will open up new possibilities for planet searches in/around (moderately) close binaries. Thanks to their high photometric precision and continuous monitoring of rich stellar fields, the recently launched CoRoT[1] and Kepler[2] missions will initiate large-scale planet searches around eclipsing binaries (Doyle & Deeg 2004; Ofir et al. 2009; see also the contribution by Sybilski). Alternatively, new interferometric facilities like PRIMA at the Very Large Telescope Interferometer (Delplancke 2008) or the ASTRA upgrade of the Keck Interferometer (Pott et al. 2008) will allow to extend astrometric planet searches to significantly wider and fainter binaries. The upcoming generation of high-contrast adaptive optics instruments such as HiCIAO at Subaru (Tamura et al. 2006), GPI at Gemini South (Macintosh et al. 2008), SPHERE at the Very Large Telescope (Beuzit et al. 2008) and PALM-3000/Project-1640 at Palomar (Bouchez et al. 2008) will also likely be used to carry out systematic searches for giant planets in some types of moderately close binaries. Gathering together the results from all these different surveys we will then have pretty good answers to the two questions mentioned at the beginning of this chapter: What types of binaries do host planets in S/P/L-type orbits?, and Are such planets common or rare?

As surveys progress and diversify, the conviction that planets are common objects in the universe continually strengthen. In addition to the encouraging observational results obtained so far on circumstellar giant planets, theoretical studies support the existence of low-mass planets in many binary systems (e.g. Thébault et al. 2006; Haghighipour & Raymond 2007; Quintana et al. 2007; see also the contribution by Marzari). Similarly, circumbinary planets are expected to be quite common (e.g. Quintana & Lissauer 2006; Pierens & Nelson 2007; Scholl et al. 2007; Pierens & Nelson 2008). Observational programs targeting (moderately) close binaries thus promise additional exciting results to come. Since a full understanding of planet formation must address the issue of circumstellar and circumbinary planets, these programs are an essential part of today's research on extrasolar planets.

[1]http://smsc.cnes.fr/COROT/
[2]http://kepler.nasa.gov

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